

Higgs exotic decays in general NMSSM with self-interacting dark matter

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Abstract

Under current LHC and dark matter constraints, the general NMSSM can have self-interacting dark matter to explain the cosmological small structure. In this scenario, the dark matter is the light singlino-like neutralino (χ) which self-interacts through exchanging the light singlet-like scalars (h_1, a_1). These light scalars and neutralinos inevitably interact with the 125 GeV SM-like Higgs boson (h_{SM}), which cause the Higgs exotic decays $h_{SM} \rightarrow h_1 h_1, a_1 a_1, \chi \chi$. We first demonstrate the parameter space required by the explanation of the cosmological small structure and then display the Higgs exotic decays. We find that in such a parameter space the Higgs exotic decays can have branching ratios of a few percent, which should be accessible in the future e^+e^- colliders.

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I. INTRODUCTION

The Λ CDM cosmological model (Λ Cold Dark Matter) can successfully describe the large-scale structure of the Universe (> 1 Mpc) and the Cosmic Microwave Background (CMB). Despite the success in describing the large-scale structure, several recent observations at galactic or smaller scales fail to be explained [1], such as the problems of *missing satellites* [2], *cusp vs core* [3] and *too big to fail* [4]. These issues strongly indicate that dark matter (DM) should not be composed of cold collisionless particles, and instead may have a richer structure involving nontrivial self-interactions. In particular, the self-interacting dark matter with a light force carrier ($\lesssim 100$ MeV) may have a non-trivial velocity-dependent scattering cross section, which gives rise to the appropriate cross sections for all of the small scales (the dwarf size, the Milky Way size as well as the galaxy cluster size) [5–7]. Note that there could be small-scale power suppression due to self-interacting dark radiation (which could also lead to dark acoustic oscillations) and/or late-kinetic decoupling. [8]

Such a self-interacting dark matter can be naturally achieved in the general singlet extension of the MSSM (GNMSSM) [9–11]. In the GNMSSM, the SUSY preserving μ -term is dynamically generated by the vacuum expectation values (VEV) of a singlet superfield S , which can solve the notorious μ -problem in the MSSM. [12] In the small λ limit, the singlet sector can be almost decoupled from the electroweak symmetry breaking sector and becomes a dark sector in the theory. Due to its very weak interactions with the SM particles, the $O(1)$ GeV singlino-like dark matter dominantly annihilates into the light singlet-like scalars, which can correctly produce the DM relic density and a proper Sommerfeld enhancement factor [13–15]. Such a feature can be used to solve the small cosmological scale anomaly without conflicting with dark matter direct detection [16]. Besides, the light singlet-like scalars are essential in such a GNMSSM explanation of small structure problem. This will inevitably lead to various exotic decays of the 125 GeV SM-like Higgs boson, such as the invisible decay to dark matter and the decays to a pair of light scalars. [17] Therefore, search for these exotic decays at colliders can allow for a test of the self-interacting dark matter in the GNMSSM.

In this work, we first revisit the GNMSSM explanation of the small structure problem under current LHC data and then investigate the 125 GeV Higgs exotic decays in the allowed parameter space. We organize the content as follows. In Sec. II, we describe the general

self-interacting dark matter interactions for explaining the small cosmological scale anomaly. In Sec. III we briefly review the GNMSSM and in Sec. IV we demonstrate the parameter space of the GNMSSM required by the explanation of the small cosmological scale anomaly. In Sec. V, we show the Higgs exotic decays in such a parameter space. Sec. VI contains our conclusions.

II. SELF-INTERACTING DARK MATTER FOR SMALL SCALE STRUCTURE

To explain both large scale and small scale structures of the Universe, one can introduce the self-interacting DM scenario, in which the interactions between DM and SM particles can be summarized as (shown in Fig. 1):

1. The cross section of the DM annihilation to the SM particles (the left diagram of Fig. 1), which at high energy determines the relic density of dark matter. At low energy this cross section can be probed by the indirect detection experiments like PAMELA [18] and AMS02 [19]. When the early universe was cooling down, the equilibrium between DM and SM particles in the thermal bath can no longer be maintained. The DM will annihilate to SM particles until the annihilation rate falls below the expansion rate of the Universe. In our following calculation, we use the standard method [20] to calculate the relativistic annihilation cross section and the degrees of freedom at the freeze-out temperature.
2. The direct DM elastic scattering off the SM particles (the middle diagram of Fig. 1), which can be probed by various underground detection experiments, such as CDMS [21], XENON [22] and LUX [23]. Due to the high sensitivity of the spin-independent (SI) measurement, we only consider the SI elastic interactions of DM (denoted by χ) and nucleon (proton and neutron), which are dominantly induced by the scalar mediator at tree level, as shown in the middle diagram of Fig.(1).
3. The non-relativistic self-scattering (the right diagram of Fig. 1), where $\ell = 0$ in the partial wave expansion gives the Sommerfeld enhancement relative to the relativistic annihilation. Such an enhancement was first proposed to explain some DM indirect detection results, like the positron excess observed by PAMELA or AMS02.[24] On

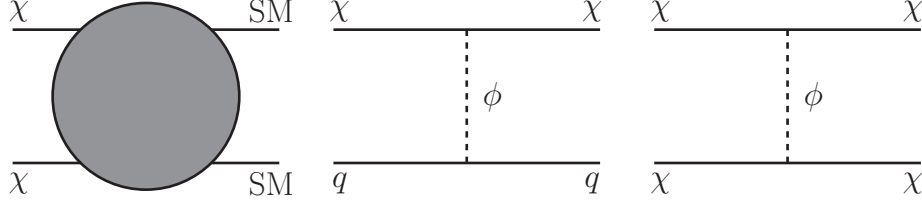


FIG. 1: Dark matter interactions: annihilation to SM particles (left panel), scattering off quarks (middle panel), and self-scattering process (right panel).

the other hand, when $\ell \lesssim 25$, the anomalies in the small cosmological scales can be successfully accounted for.

To explain the DM indirect detection results (such as the PAMELA result) and the small cosmological scale anomalies, the DM scattering cross section should be calculated at low energies, where the above interactions entangles with each other. In this case, the complete investigation of the DM properties needs to consider all the above interactions under various dark matter detection experiments. Details of this study can be found in [16]. Here we only briefly discuss the calculation of the non-relativistic self-scattering cross section.

The numerical input for the simulation of small scales is the differential cross section $d\sigma/d\Omega$, which is a function of the DM relative velocity v . Then the viscosity (or conductivity) cross section σ_V [25] can be defined as

$$\sigma_V = \int d\Omega \sin^2 \theta \frac{d\sigma}{d\Omega}. \quad (1)$$

This formula is valid for the Majorana-fermion DM candidate. The weight of $\sin^2 \theta$ in the integral is needed since both forward and backward scatterings amplitudes will diverge. Such singularities correspond to the poles in the t - and u -channel diagrams for the identical DM candidate. Within the resonance region, σ_V must be computed by solving the Schrödinger equation with the partial wave expansion method:

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dR_\ell}{dr} \right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2m_r V(r) \right) R_\ell = 0. \quad (2)$$

The total wave function of the spin-1/2 fermionic DM must be antisymmetric with respect to the interchange of two identical particles. Then the spatial wave function should be symmetric (antisymmetric) when the total spin is 0 (1). The viscosity cross section can be

reduced to two variables:

$$\frac{d\sigma_{VS}}{d\Omega} = |f(\theta) + f(\pi - \theta)|^2 = \frac{1}{k^2} \left| \sum_{\ell(\text{EVEN number})}^{\infty} (2\ell + 1)(\exp(2i\delta_l) - 1)P_\ell(\cos \theta) \right|^2 \quad (3)$$

$$\frac{d\sigma_{VA}}{d\Omega} = |f(\theta) - f(\pi - \theta)|^2 = \frac{1}{k^2} \left| \sum_{\ell(\text{ODD number})}^{\infty} (2\ell + 1)(\exp(2i\delta_l) - 1)P_\ell(\cos \theta) \right|^2 \quad (4)$$

Using the orthogonality relation of the Legendre polynomials, we can have

$$\frac{\sigma_{VS}k^2}{4\pi} = \sum_{\ell(\text{EVEN number})}^{\infty} 4 \sin^2(\delta_{\ell+2} - \delta_\ell)(\ell + 1)(\ell + 2)/(2\ell + 3), \quad (5)$$

$$\frac{\sigma_{VA}k^2}{4\pi} = \sum_{\ell(\text{ODD number})}^{\infty} 4 \sin^2(\delta_{\ell+2} - \delta_\ell)(\ell + 1)(\ell + 2)/(2\ell + 3). \quad (6)$$

When the partial wave ℓ grows up, it can be seen that σ_V will converge to a static value as the phase shift δ_ℓ approaches to a same value. We adopt the numerical method in [26] to calculate all these cross sections. In our following analysis, we assume that the DM scatters randomly. Thus the average cross section will be

$$\sigma_V = \frac{1}{4}\sigma_{VS} + \frac{3}{4}\sigma_{VA}. \quad (7)$$

III. THE GENERAL SINGLET EXTENSION OF MSSM (GNMSSM)

The superpotential of the general NMSSM is given by [27]

$$W = W_{\text{Yukawa}} + (\mu + \lambda \hat{S}) \hat{H}_u \cdot \hat{H}_d + \xi_F \hat{S} + \frac{1}{2} \mu' \hat{S}^2 + \frac{\kappa}{3} \hat{S}^3 \quad (8)$$

where \hat{H}_u and \hat{H}_d are the two Higgs doublets, \hat{S} is the gauge singlet. The terms $\sim \mu, \mu'$ are supersymmetric mass terms, and ξ_F of dimension $mass^2$ parameterizes the (supersymmetric) tadpole term. The Yukawa couplings of the quark and lepton superfields are given as

$$W_{\text{Yukawa}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{H}_d \cdot \hat{Q} \hat{D}_R^c + h_e \hat{H}_d \cdot \hat{L} \hat{E}_R^c \quad (9)$$

where the Yukawa couplings h_u , h_d , h_e and the superfields \widehat{Q} , \widehat{U}_R^c , \widehat{D}_R^c , \widehat{L} and \widehat{E}_R^c should be understood as matrices and vectors in family space, respectively. The corresponding soft SUSY breaking masses and couplings are

$$\begin{aligned}
-\mathcal{L}_{\text{soft}} = & m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + m_Q^2 |Q|^2 + m_U^2 |U_R^2| \\
& + m_D^2 |D_R^2| + m_L^2 |L|^2 + m_E^2 |E_R^2| \\
& + (h_u A_u Q \cdot H_u U_R^c - h_d A_d Q \cdot H_d D_R^c - h_e A_e L \cdot H_d E_R^c \\
& + \lambda A_\lambda H_u \cdot H_d S + \frac{1}{3} \kappa A_\kappa S^3 + m_3^2 H_u \cdot H_d + \frac{1}{2} m_S'^2 S^2 + \xi_S S + \text{h.c.}) . \quad (10)
\end{aligned}$$

Clearly, if $\mu = \mu' = \xi_F = 0$, the \mathcal{Z}_3 NMSSM superpotential is obtained as

$$W_{\text{NMSSM}} = \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 \quad (11)$$

and the parameters m_3^2 , $m_S'^2$ and ξ_S in (10) are vanishing. Then, a VEV s of \widehat{S} of the order of the weak or SUSY breaking scale generates an effective μ -term with

$$\mu_{\text{eff}} = \lambda s \quad (12)$$

The neutral physical Higgs fields (with index R for the CP-even and index I for the CP-odd states) can be obtained by expanding the full scalar potential around the real neutral vevs v_u , v_d and s

$$H_u^0 = v_u + \frac{H_{uR} + iH_{uI}}{\sqrt{2}}, \quad H_d^0 = v_d + \frac{H_{dR} + iH_{dI}}{\sqrt{2}}, \quad S = s + \frac{S_R + iS_I}{\sqrt{2}} . \quad (13)$$

It is convenient to define, together with μ_{eff} as in (12),

$$B_{\text{eff}} = A_\lambda + \kappa s, \quad \widehat{m}_3^2 = m_3^2 + \lambda(\mu' s + \xi_F) \quad (14)$$

where we have used the convention $\mu = 0$. B_{eff} plays the role of the MSSM-like B -parameter, and \widehat{m}_3^2 vanishes in the NMSSM. After the spontaneously symmetry breaking, we can have the mass spectrum of all the particles. The tree level Higgs mass matrices can be obtained by expanding the full Higgs potential around the real neutral vevs v_u , v_d and s as in (13). Then, the elements of the 3×3 CP-even mass matrix \mathcal{M}_S^2 in the basis (H_{dR}, H_{uR}, S_R) after

the elimination of $m_{H_d}^2$, $m_{H_u}^2$ and m_S^2 can be read as

$$\begin{aligned}
\mathcal{M}_{S,11}^2 &= g^2 v_d^2 + (\mu_{\text{eff}} B_{\text{eff}} + \hat{m}_3^2) \tan \beta , \\
\mathcal{M}_{S,22}^2 &= g^2 v_u^2 + (\mu_{\text{eff}} B_{\text{eff}} + \hat{m}_3^2) / \tan \beta , \\
\mathcal{M}_{S,33}^2 &= \lambda(A_\lambda + \mu') \frac{v_u v_d}{s} + \kappa s (A_\kappa + 4\kappa s + 3\mu') - (\xi_S + \xi_F \mu') / s , \\
\mathcal{M}_{S,12}^2 &= (2\lambda^2 - g^2) v_u v_d - \mu_{\text{eff}} B_{\text{eff}} - \hat{m}_3^2 , \\
\mathcal{M}_{S,13}^2 &= \lambda(2\mu_{\text{eff}} v_d - (B_{\text{eff}} + \kappa s + \mu') v_u) , \\
\mathcal{M}_{S,23}^2 &= \lambda(2\mu_{\text{eff}} v_u - (B_{\text{eff}} + \kappa s + \mu') v_d) .
\end{aligned} \tag{15}$$

After diagonalization, we can have three CP-even mass eigenstates, which are denoted as h_1, h_2, h_3 , respectively. The element of the CP-odd mass matrix $\mathcal{M}_P'^2$ is 3×3 matrix in the basis (H_{dI}, H_{uI}, S_I) . $\mathcal{M}_P'^2$ usually contains a massless Goldstone mode G . We rotate this mass matrix into the basis (A, G, S_I) , where $A = \cos \beta H_{uI} + \sin \beta H_{dI}$. After absorbing the Goldstone mode, the remaining 2×2 mass matrix \mathcal{M}_P^2 in the basis (A, S_I) has the following elements

$$\begin{aligned}
\mathcal{M}_{P,11}^2 &= \frac{2(\mu_{\text{eff}} B_{\text{eff}} + \hat{m}_3^2)}{\sin 2\beta} , \\
\mathcal{M}_{P,22}^2 &= \lambda(B_{\text{eff}} + 3\kappa s + \mu') \frac{v_u v_d}{s} - 3\kappa A_\kappa s - 2m_S'^2 - \kappa \mu' s - \xi_F \left(4\kappa + \frac{\mu'}{s} \right) - \frac{\xi_S}{s} , \\
\mathcal{M}_{P,12}^2 &= \lambda(A_\lambda - 2\kappa s - \mu') v .
\end{aligned} \tag{16}$$

Similarly, we can obtain two mass eigenstates denoted as (a_1, a_2) . Note that we can set $A_\lambda - 2\kappa s - \mu' = 0$ to forbid the mixing between the doublet and the singlet. In the neutralino sector, the neutral gaugino λ_1 and λ_2^3 mix with the neutral higgsinos $\psi_d^0, \psi_u^0, \psi_S$, which generates a symmetric 5×5 mass matrix \mathcal{M}_0 . In the basis $\psi^0 = (-i\lambda_1, -i\lambda_2^3, \psi_d^0, \psi_u^0, \psi_S)$, the resulting mass terms in the Lagrangian can be read as

$$\mathcal{L} = -\frac{1}{2}(\psi^0)^T \mathcal{M}_0(\psi^0) + \text{h.c.} \tag{17}$$

where

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s + \mu' \end{pmatrix}, \quad (18)$$

Here M_1 , M_2 are the soft mass parameters of the gauginos. After diagonalization, we can have five mass eigenstates $\chi_{1,\dots,5}$. If the neutralino (χ_1) is the lightest supersymmetric particle (LSP), it will be a good candidate of DM. In the GNMSSM, the self-interaction dark matter scenario can be realized if the LSP is singlino-like and h_1 is light enough and serve as be the mediator between the DM scattering [16]. In the following section we will revisit such a scenario under the current LHC constraints and investigate the the Higgs exotic decays in the visible parameter space of explaining the small structure anomalies.

IV. SELF-INTERACTING DARK MATTER IN THE GNMSSM

From the neutralino mass matrix in Eq.(18), we can see that the GNMSSM singlino mass is mainly determined by the parameters μ' and κ . By tuning these two parameters, the very light singlino-like LSPs can dominantly annihilate to the singlet-like Higgs bosons and satisfy the requirements of relic abundance and direct detections [16]. Here it should be mentioned that the correlation between the singlino sector and the singlet Higgs bosons sector are relaxed by the extra parameter μ' in the GNMSSM, which is different from the situation in \mathcal{Z}_3 -NMSSM *

In our numerical calculations, we use the newest version of package NMSSMTools [28] to perform the scan of the parameter space. All the mass input parameters are defined at the

* In the \mathcal{Z}_3 -NMSSM, the masses of the singlino and the singlet Higgs bosons are strongly related by the same parameter κ . Thus, when $\kappa \ll \lambda$, [29] the correct relic abundance of the very light singlino dark matter is obtained by annihilating to the SM fermions via the very light (several MeV) singlet CP-odd Higgs boson. However, such a light singlet scalar will greatly enhance the DM-nucleon SI cross section and is disfavored by the current dark matter direct detection. So, it hardly realizes the self-scattering dark matter for the cosmological small structure in the \mathcal{Z}_3 NMSSM.

electroweak scale. We choose the input parameters of the Higgs sector as

$$\lambda, \kappa, \tan\beta, \mu_{\text{eff}}, A_\lambda, A_\kappa, m_3^2, \mu', m_S'^2, \xi_F, \xi_S. \quad (19)$$

Then, we scan the dimensionless parameters in the range

$$0.005 < |\lambda, \kappa| < 0.5, \quad 1 < \tan\beta < 50$$

and all the other mass dimension parameters in the range

$$(-2\text{TeV}, 2\text{TeV}).$$

To obtain the very light singlino-like DM and the singlet-like Higgs bosons, we require

$$\xi_S \sim \lambda(A_\lambda + \mu')v_u v_d - \kappa s^2(A_\kappa + 4\kappa s + 3\mu') - \xi_F \mu', \quad (20)$$

$$m_S'^2 \sim \frac{1}{2} \left[\lambda(B_{\text{eff}} + 3\kappa s + \mu') \frac{v_u v_d}{s} - 3\kappa A_\kappa s - \kappa \mu' s - \xi_F \left(4\kappa + \frac{\mu'}{s} \right) - \frac{\xi_S}{s} \right], \quad (21)$$

$$\mu' \sim -2\kappa s. \quad (22)$$

Also, we require

$$A_\lambda = 2\kappa s + \mu', \quad (23)$$

to forbid the mixing between the CP-odd doublet and the singlet Higgs bosons. The gaugino input parameters M_1, M_2, M_3 are scanned in the range of $(-1\text{TeV}, 1\text{TeV})$. In order to give a 125 GeV SM Higgs boson, we scan the third generation squark mass parameters $m_{Q_{3L}}, m_{U_{3R}}$ and $m_{D_{3R}}$ in the range of $(-5\text{TeV}, 5\text{TeV})$. The first two generation squark and slepton mass parameters are fixed at 5 TeV. Finally, we tune the parameter A_κ slightly to give a light h_1 at order of 10 MeV. In our scan, we impose the following constraints:

- The SM-like Higgs mass in the range of 123-127 GeV;
- The thermal relic density of the lightest neutralino in the 2σ range of the Planck value [30];
- The LEP-I bound on the invisible Z -decay, $\Gamma(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 1.76 \text{ MeV}$, and the LEP-II

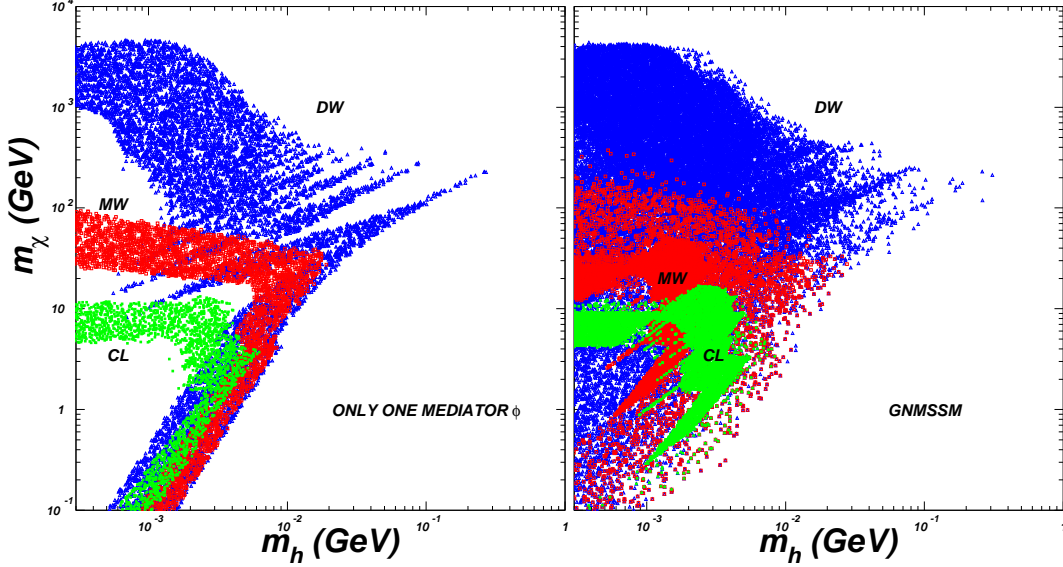


FIG. 2: The survived points under the constraints of relic density and the scattering cross section in case of $\lambda = 0$. The blue points are the points satisfy the simulation in the Dwarf scale ($\sigma/m_\chi \sim 0.1 - 10 \text{ cm}^2/\text{g}$, the characteristic velocity is 10 km/s.) The red points are the points satisfy the simulation in the Milky Way ($\sigma/m_\chi \sim 0.1 - 1 \text{ cm}^2/\text{g}$, the characteristic velocity is 200 km/s.) The green points are the points satisfy the simulation in the Milky Way ($\sigma/m_\chi \sim 0.1 - 1 \text{ cm}^2/\text{g}$, the characteristic velocity is 1000 km/s.)

upper bound on $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_i^0) < 5 \times 10^{-2} \text{ pb}$ for $i > 1$, as well as the lower mass bounds on the sparticles from the direct searches at LEP and the Tevatron;

- The constraints from the LHEP-II direct search for the Higgs boson exotic decays, including the decay modes $h \rightarrow h_1 h_1, a_1 a_1 \rightarrow 4f$;
- The constraints from B -physics: $B \rightarrow X_s \gamma$, $B^+ \rightarrow \tau^+ \nu$, $\Upsilon \rightarrow \gamma a_1$, the a_1 - η_b mixing and the mass difference ΔM_d and ΔM_s .

In Fig. 2, we show the survived points under the constraints of relic density and scattering cross section in case of $\lambda = 0$. The left panel shows the results for one mediator in the simplified model [31], while the right panel shows the results of the GNMSSM. We can see that the simulation of small structure gives a stringent constraint on the parameter space for the self-interacting DM, in particular for one light mediator case. The survival parameter space in the GNMSSM is larger than the simple model of one mediator. The main reason is that in the DM self-interaction model [26] DM can only annihilate into hh via t -channel and u -channel while in the GNMSSM DM can annihilate into hh , ha and aa via t -channel,

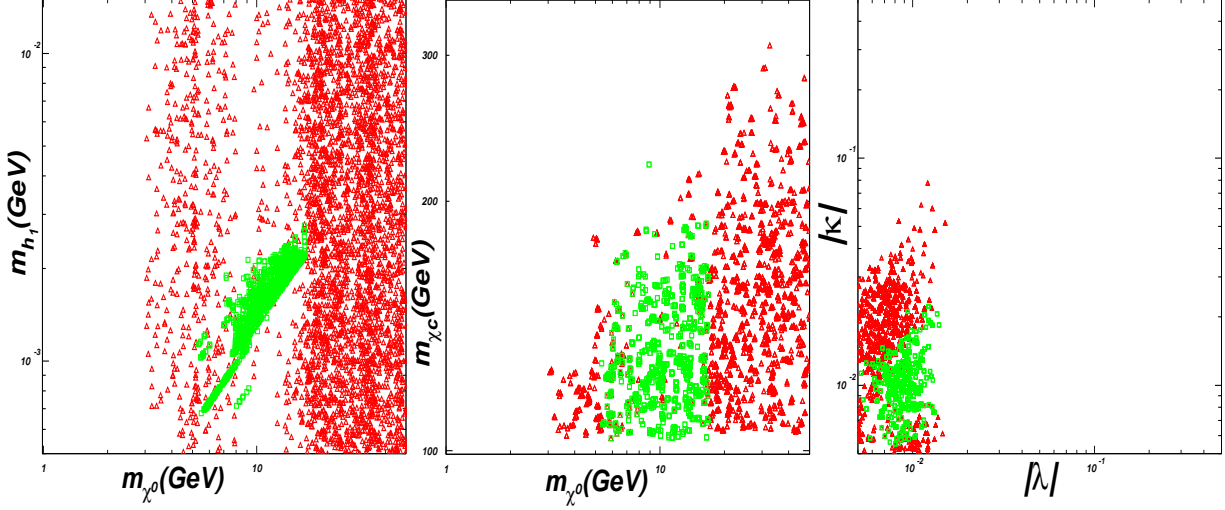


FIG. 3: Scatter plots of the samples which satisfy the current experimental constraints except the direct detection limits of dark matter. The \square (green) and \triangle (red) samples can and cannot explain the small-scale cosmic structure, respectively.

u -channel and s -channel.

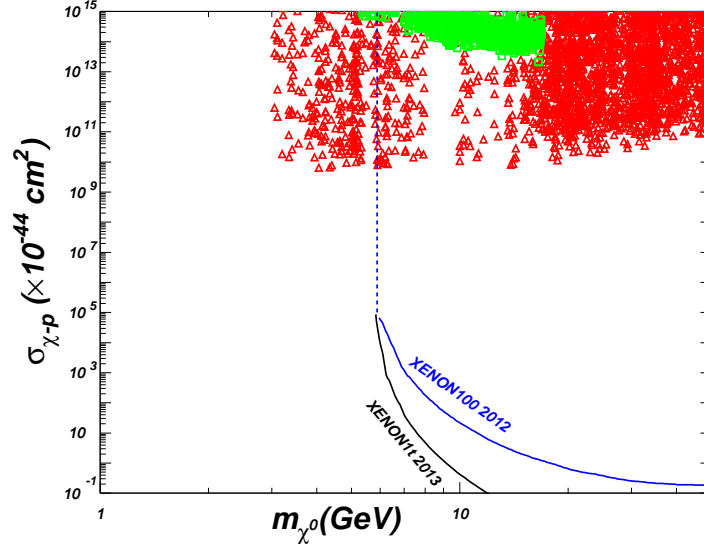


FIG. 4: Same as Fig. 3, but showing the spin-independent cross section of dark matter-nucleon scattering. The curves are the current limits of dark matter direct detections, which can exclude most samples but have no sensitivity to ultra-light dark matter.

In Fig. 3, we present the scatter plots of the survived samples which can satisfy the current experimental constraints and can explain the small-scale cosmic structure. From Fig. 3, it can be seen that the mass of the light CP-even singlet-like Higgs boson has to be

in the range of (0.6, 3) MeV in order to explain the small structure simulations. The mass of the singlino-like DM is required to be in the range of (5, 11) GeV. Besides, the couplings λ and κ are bounded below 0.02 and κ can be much larger than λ . We also note that the chargino mass $m_{\chi_1^\pm}$ is strongly constrained and should be less than 210 GeV.

In Fig. 4, we display the scatter plots by showing the spin-independent cross section of dark matter-nucleon scattering. We can see that the cross section is greatly enhanced by the light mediator h_1 with mass about 10 MeV. The current direct detection experiments, such as XENON 2012, have already excluded most of the samples when the dark matter is not so light. However, the ultra-light dark matter can still be allowed because the direct detections have no sensitivity to ultra-light dark matter.

V. HIGGS EXOTIC DECAYS IN THE GNMSSM WITH SELF-SCATTERING DARK MATTER

Now we display in Fig. 5 the Higgs exotic decays in the GNMSSM parameter space which can satisfy the current experimental constraints (including the direct detection limits of dark matter) and can explain the small-scale cosmic structure. From Fig. 5 we can see that the branching ratios of these channels become larger with the increase of κ . This is because that the branching ratios of these decay channels are dominantly determined by the Higgs self-coupling parameter κ for the fixed masses of h_1 , a_1 and χ_1 . However, it should be noted that the small structure simulations require a small κ so that the branching ratios of the decay channels $h_{SM} \rightarrow h_1 h_1, a_1 a_1$ can only reach about 3%, while the invisible decay can only reach 0.5%.

In Fig. 6, we show the cross sections of $\sigma(e^+e^- \rightarrow Zh_{SM}) \times Br(h_{SM} \rightarrow XX)$ ($X = h_1, a_1, \chi$) for $\sqrt{s} = 250$ GeV. From Fig. 6, we can see that the cross section of $e^+e^- \rightarrow Zh_{SM} \rightarrow Zh_1 h_1$ can maximally reach 6 fb, which corresponds to 3×10^4 events for the highest luminosity $\mathcal{L} = 5000 \text{ fb}^{-1}$ at an e^+e^- collider. When $2m_e < m_{h_1}$, the CP-even h_1 will dominantly decay to the e^+e^- final states. Then the most promising channel of searching for such a light CP-even Higgs boson will be $e^+e^- \rightarrow Zh_{SM} \rightarrow Zh_1 h_1 \rightarrow 2j + 4\ell$ at an e^+e^- collider. While the cross section of $e^+e^- \rightarrow Zh_{SM} \rightarrow Za_1 a_1$ can maximally reach 3 fb and the light CP-odd a_1 will mainly decay to $b\bar{b}$, which leads to a distinctive signature

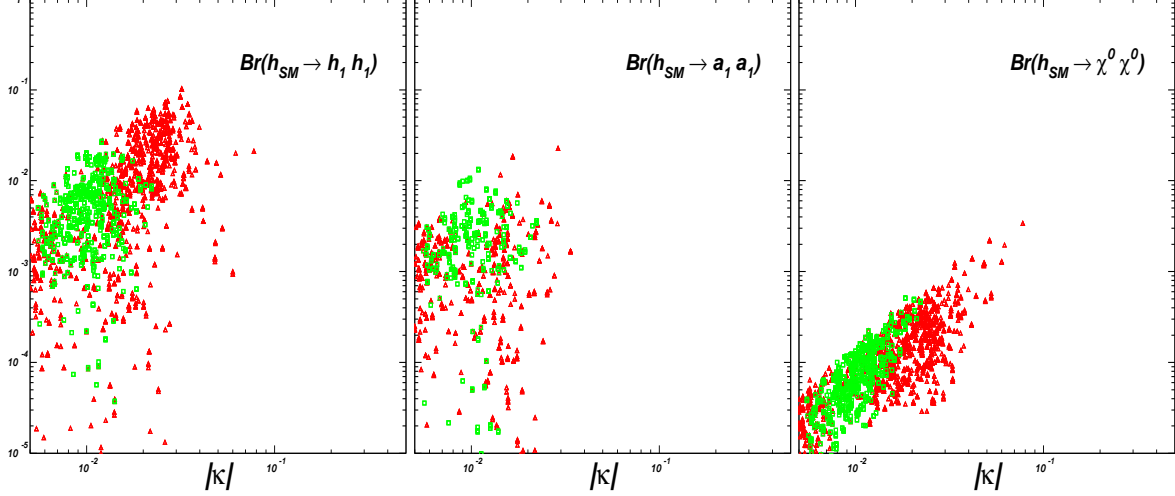


FIG. 5: Same as Fig. 3, but showing the branching ratios of the exotic decays of the 125 GeV SM-like Higgs boson.

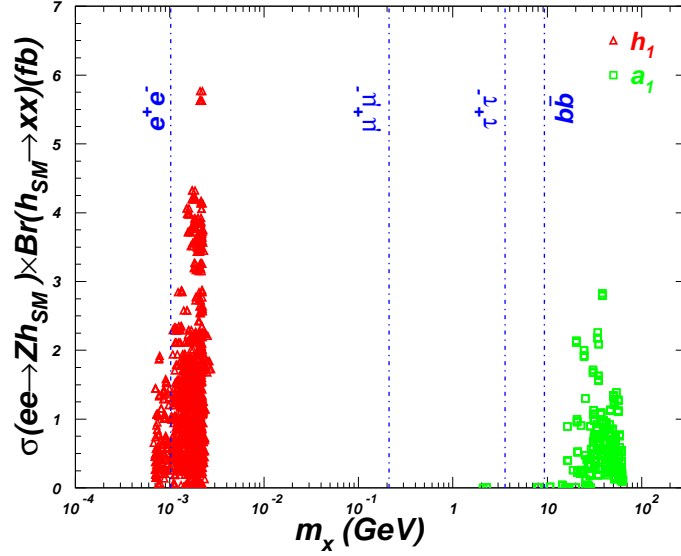


FIG. 6: Same as Fig. 3, but showing the cross sections of $\sigma(e^+e^- \rightarrow Zh_{SM}) \times Br(h_{SM} \rightarrow XX)$ for $\sqrt{s} = 250$ GeV, where $X = h_1, a_1, \chi$. The vertical lines (from left to right) correspond to the mass thresholds of e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$ and $b\bar{b}$ final states, respectively.

of $2\ell + 4b$ at an e^+e^- collider. [†]. Due to the clean environment, with the mass window cut $|m_{4b} - m_{h_{SM}}| < 10$ GeV, such a signature may be observed at a future e^+e^- collider.

[†] The observability of light a_1 through the process $pp \rightarrow Vh_{SM} \rightarrow 2\ell + 4b$ has been investigated in [33–35] and is found to reach 3σ if $Br(h_{SM} \rightarrow a_1 a_1) > 15\%$ at LHC with a luminosity $\mathcal{L} = 300 \text{ fb}^{-1}$ [35].

VI. CONCLUSIONS

We revisited the general NMSSM which can have self-interacting dark matter to explain the cosmological small structure. In this scenario, the dark matter is the ultra-light singlino-like neutralino (χ) which self-interacts through exchanging the ultra-light singlet-like scalars (h_1, a_1). Since these light scalars and neutralinos inevitably interact with the 125 GeV SM-like Higgs boson (h_{SM}), the Higgs will have exotic decays $h_{SM} \rightarrow h_1 h_1, a_1 a_1, \chi\chi$. We first showed the parameter space required by the explanation of the cosmological small structure and then displayed the Higgs exotic decays. We found that in such a parameter space the Higgs exotic decays can have branching ratios of a few percent, which could be accessible in the future e^+e^- colliders.

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